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14. ABSTRACT

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Angle and Polarization Dependent Characteristics of Colloidal Quantum Dot Absorption in Fano Filters on Flexible Substrates

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ABSTRACT

We report theoretical and experimental investigations of infrared absorption characteristics for PbSe colloidal quantum dots in defect-free photonic crystal (PC) cavities, via Fano resonances. Angle and polarization independent transmission and absorption are feasible for surface normal incident beams with dispersion engineered modal design. Experimental demonstration was done on patterned single crystalline silicon nanomembranes (SiNMs) transferred on glass and on flexible PET substrates, with PbSe QDs backfilled into the air holes of the patterned SiNMs. These findings enable the design of spectrally selective photodetectors at near infrared regime with the desired angle and polarization properties.

Keywords: colloidal quantum dots, Fano resonances, Photonic crystals, Infrared photodetectors.

1 INTRODUCTION

Infrared (IR) photodetectors with controllable spectral resolution and polarization properties, from near to far infrared spectral regime, are highly desirable for absorption spectroscopy gas sensing and hyper-spectral imaging applications. Owing to the light-matter interaction modifications, spectrally selective absorption can be achieved in photonic crystal (PC) cavities. In the defect photonic crystal cavities, strong coupling from in-plane defect mode to vertical radiation mode can be utilized to significantly enhance absorption [1, 2]. On the other hand, in the defect-free photonic crystal cavities, absorption enhancement was obtained through strong light coupling effect between in-plane discrete guided resonances and vertical continuum free-space radiation modes. This coupling effect results in asymmetrical or symmetrical sharp peaks/dips in the transmission response, called Fano resonances [3-5].

Fano effect based on photonic crystal can be easily manipulated with several design parameters, such as lattice configurations , air hole geometry, the ratio of the air hole radius to the lattice constant (r/a), the refractive index and slab thickness, and the absorption layer properties [6, 7]. Therefore, Fano resonance photonic crystal structures have great potential for many optoelectronic device applications: filters [8-12], modulators [13, 14], sensors [15, 16], thermal radiation spectral and spatial control [17], broadband reflectors [6, 18], surface emitting lasers [19], bistable and other nonlinear optical devices [20, 21]. In addition, high index contrast was not necessary in Fano resonance function [22]. Recently, we investigated enhanced infrared absorption of infrared photodetectors for symmetrical and asymmetrical photonic crystal structure based on Fano resonance [23].

Epitaxial quantum dot based IR photodetectors (QDIPs) have made significant progresses in the past decade [24-26]. Due to the three dimensional quantum confinements, the QD itself exhibited unique absorption spectra. Both epitaxial and colloidal QDs can be incorporated in infrared photodetector design for the desired spectral coverage [27]. The interaction of photonic crystal cavities and semiconductor QDs can lead to engineered spectral resolution with multi-spectral coverage in IR photodetectors [1].

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Here, we report theoretical and experimental investigations of the infrared absorption characteristics for PbSe colloidal quantum dots in defect-free photonic crystal cavities, via Fano resonances. Angle and polarization independent transmission and absorption are feasible for surface normal incident beams with dispersion engineered modal design. The center absorption wavelength of PbSe QD was near 1550 nm. Experimental demonstration was done on patterned single crystalline silicon nanomembranes (SiNMs) transferred on glass and on flexible polyethylene terephthalate (PET) substrates, with PbSe QDs backfilled into the air holes of the patterned SiNMs. The Fano resonance was red-shifted due to the change of the refractive index in the air hole region of the patterned SiNMs with back-filled PbSe QDs. The absorption also changed at the Fano resonance location due to the interaction between PbSe QDs and Fano resonances. These findings enable the design of spectrally selective photodetectors at near infrared regime with the desired spectral, angle and polarization properties.

2 FANO FILTER DESIGN FABRICATION AND CHARACTERISATION

The Fano filter design is based on three-dimensional (3D) finite-difference timedomain (FDTD) technique. With the target filter operation wavelength (λ) of 1550 nm, airhole radius (r) and the lattice constant (a) are chosen 108nm and 600nm respectively. The starting material is a silicon-on-insulator (SOI) wafer with a 260 nm top Si layer. The PC was first fabricated on SOI wafer using a standard e-beam lithography technique which was followed by plasma reactive-ion etching (RIE) through top Si layer . Shown in Figure 1 (a)- (c) are different resolution scanning electron micrographs (SEM) of the fabricated large area PC patterns (~ 5x5 mm), where the high-quality uniform patterns are formed with optimised fabrication processes.

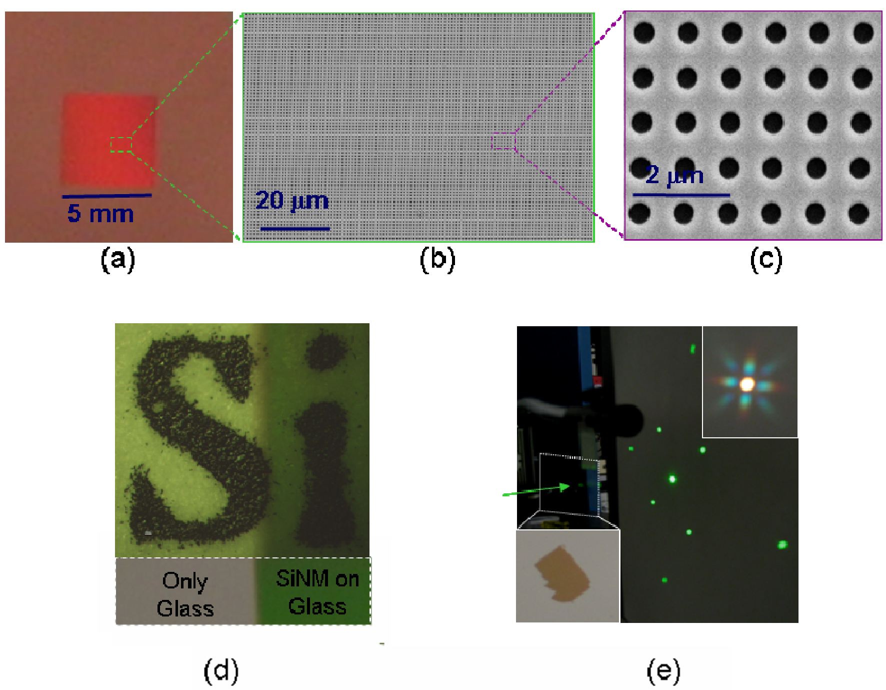

Figure 1 (a)-(c) SEM images of 5x5mm square photonic crystal pattern on SOI; (d) Image under microscope of transferred silicon pattern on glass; (e) Measured diffraction patterns through the SiNM on PET sample with either a cw green laser source or a broadband QTH lamp source (top inset). The micrograph of the transferred SiNM on PET is shown in the bottom inset (center golden colored piece).

The patterned PC SOI structure was subsequently transferred onto a glass or a polyethylene terephthalate (PET) substrate, based on a modified wet transfer process [28-30]. The structure was immersed in aqueous diluted HF solution for several hours to etch away 3 µm-thick buried oxide (BOX) layer on the Si substrate selectively. Once the top patterned PC SiNM was completely released, it was rinsed in DI water and transferred onto glass or PET

flexible plastic substrates. The transferred patterned SiNM is semi-transparent, as shown in Figure 1 (d). The high-quality SiNM PC patterns were further verified with diffraction pattern measurements, as shown in Figure 1 (e), with the inset shown the transferred PC patterned SiNM on the glass substrate under test. A well-defined diffraction pattern was observed with a continuous- wave green laser source passing through the SiNM on the glass substrate. Also shown to the right of Figure 1 (e) is the highly ordered diffraction pattern obtained with a focused broadband quartz tungsten halogen (QTH) light source passing though the device.

Shown in Figure 2 (a) is the light incident scheme. The incident light angle is specified by two polar angles, the colatitude angle θ (angle off surface normal direction) and the azimuth angle ϕ (angle off +x direction). The incident polarization (E-vector) angle Ψ is defined as the angle off the positive x-axis to the projection of polarization direction. Measured Fano filter transmission characteristic was shown in Figure 2 (b) as the red curve. The dominant Fano resonance was found at 1562 nm which was exactly matched with our design value shown in blue curve. Another small dip at around 1420 nm was also confirmed by simulation. These dips resulting from abrupt phase jump can be further optimized to design for high Q filters. With fixed azimuth angle and polarization angle ($\phi=0^0$ and $\Psi=0^0$), the measured 2D incident colatitude angle θ dependent transmission intensity contour was shown in Figure 2(c). Under such situation, the angle-independent transmission was found for the dominant Fano mode (at $\lambda =$ 1562 nm). The other modes exhibited different behavior and quick moved towards longer wavelength region with increased angle θ. The correlated dispersion plot was shown in Figure 2(d). Experimental and simulation data agreed well with each other.

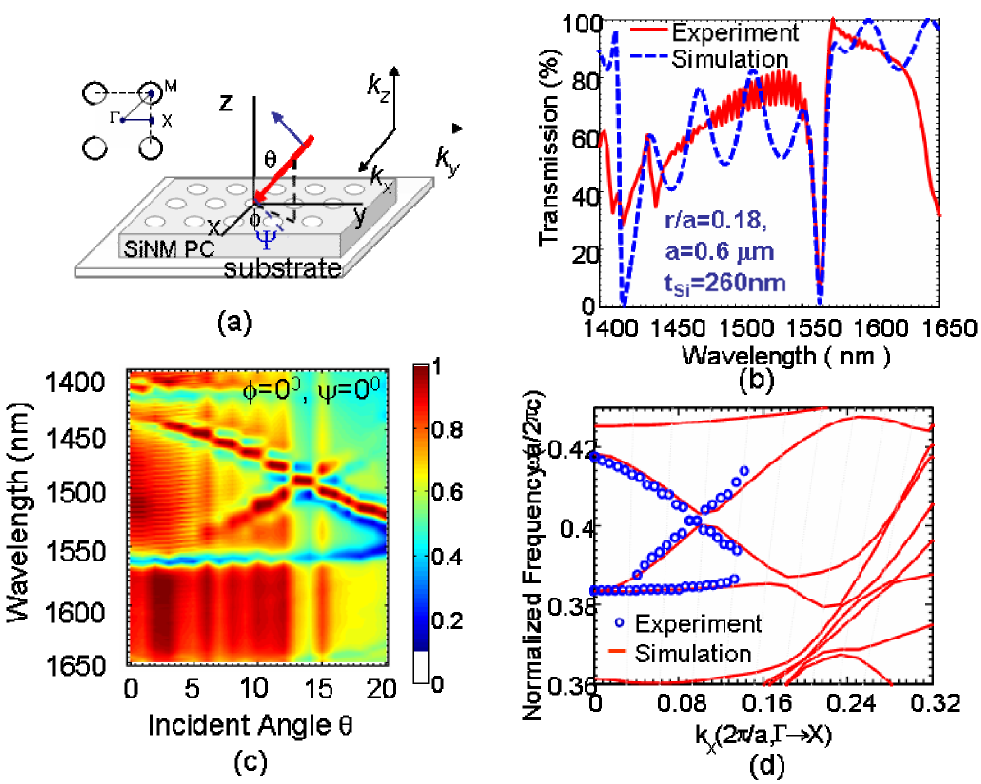

Figure 2 (a) Schematic of patterned SiNMs transferred on substrate,with the beam incident angles defined. The PC lattice and Brillion zone symmetric points Γ, X, and M in k-space are also shown in the inset; (b) Measured and simulated surface normal transmission ($\theta=0°$); (c) Measured 2D angle dependent transmission intensity contour plot for different incident angle θ with $\psi=0°$, $\phi=0°$; (d) Simulated dispersion plot (red curves) along ΓX direction, along with measured plot(blue dots) for different incident angle θ with $\psi=0°$, $\phi=0°$

3 COLLOIDAL QD IN FANO FILTER

We have reported earlier encapsulated photonic crystals by backfilling of the nanoparticles into planar 2D air-hole PCS waveguide [31], as shown in Figure 3(a). Such encapsulated PCs can be used for efficient electrical injection in photonic crystal surface-emitting lasers. Recently, colloidal PbSe and CdSe quantum dots become more promising because of high quantum efficiency and wide/tunable spectral coverage [32, 33]. Shown in Figure 3(b), as an example, 9nm PbSe QDs infiltrated into the Si PCS air holes by soaking the Si PCS structure in the QD solution. Colloidal PbSe QDs used here were prepared by a noncoordinating solvent technique in Prof. Xu's group [34], with target absorption peak around 1510 nm, as shown in Figure 4.

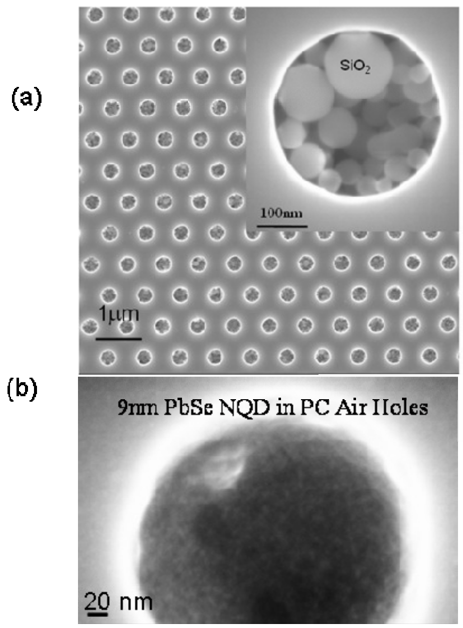

Figure 3 SEM images of self –assembly nanoparticles filled in the photonic crystal (a) 40nm SiO_2 nanoparticales in 300nm air holes; (b) 9nm colloidal PbSe quantum dots in air holes.

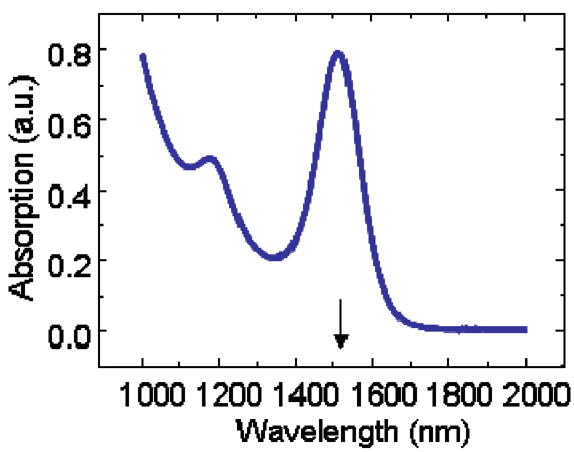

Figure 4 Measured absorption spectra of colloidal PbSe quantum dots in toluene solution

The PbSe QD solution drop-casted onto our first Fano filter sample on PET substrate. With surface-normal incidence, the focused light beam striked at the same location of Si PC pattern area. The measured transmission

without and with PbSe QDs were shown in Figure 5. The dominant Fano resonance dip red-shifted from 1562 nm to 1570 nm. This shift in transmitted spectra was due to the change of the refractive index in the air hole region of the patterned SiNMs when back-filled with PbSe QDs. The absorption also changed at the Fano resonance location due to the interaction between PbSe QDs and Fano resonances.

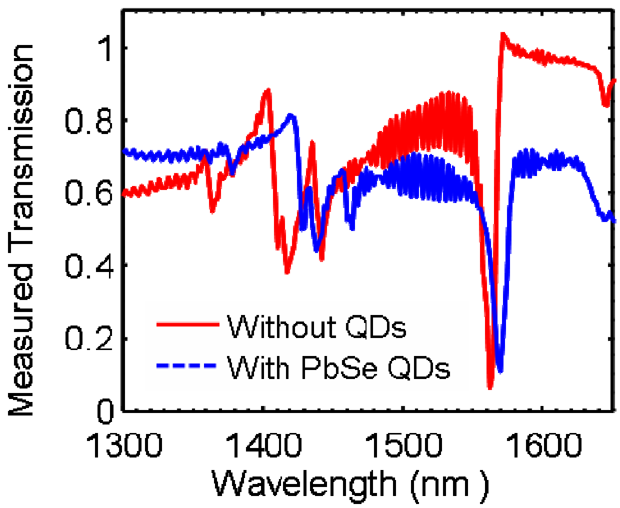

Figure 5 Meausred transmission response of SiNM on PET substrate sample before (red solid curve) and after (blue dash curve) PbSe QD drop-casting

We fitted the measurement data with the simulation results, by introducing the effective refractive index (real part of index *n*) and the extinction coefficient (*k*, imaginary part of *n*) in the air hole region. Shown in Figure 6 (a) and (b) are two fitting examples with n_{hole}=1.2+0.0342i and n_{hole}=1.2+0.1042i, respectively. The real part of effective index is found to be 1.2, which agrees well with the estimate, considering the packing density of PbSe QD in the air hole region. This fitting value results in excellent agreement in the spectra location between experiment and simulation. On the other hand, the imaginary part of the effective index seems to be complicated. Here we adapted a simplified approach by assuming a fixed extinction coefficient *k* value, which can result in a good fit at the spectral dip location only, as shown in Figure 6 (b). However, the fitting at other spectra locations is not good, which means a more accurate fitting can only be achieved by considering the spectral dependent properties of the absorption. Further work is understaking to provide a better fitting on the absorption data, which can also result in finding the absolute absorption enhancement at different spectral locations by placing PbSe QDs inside the air holes of the Fano resonant cavities.

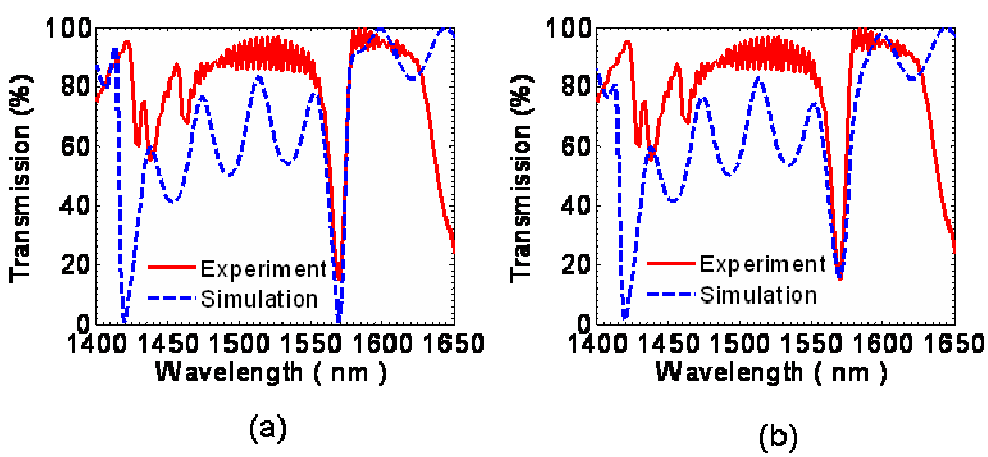

Figure 6 Measured transmission along with different fit function for the SiNM on PET substrate (a) n_{hole} =1.2+ 0.0342i; (b) n_{hole}=1.2+0.1042i.

The second set of sample on glass substrate were used for angle dependent investigation. Following the same drop-casting process, we measured the transmission spectra with incident angle θ varying from 0^0 to 20^0, while keeping the sample along ΓX direction and keeping the light polarization fixed at TM direction. The solid curves and dash curves shown in Figure 7 are transmission spectra with and without PbSe QDs, respectively. The red-shifted spectra were observed over the whole measured incident angle range, mostly due to the real part effective index change in the air hole region, as explained earlier. The dip intensity, however, is related to the absorptions at different incident angles. Further work is undertaking to calculate the spectral dependent absorption enhancement. These findings confirms the feasibility of incorporation of PbSe QDs in SiNM Fano filters for angle, polarization, and spectral-dependent infrared photodetector design.

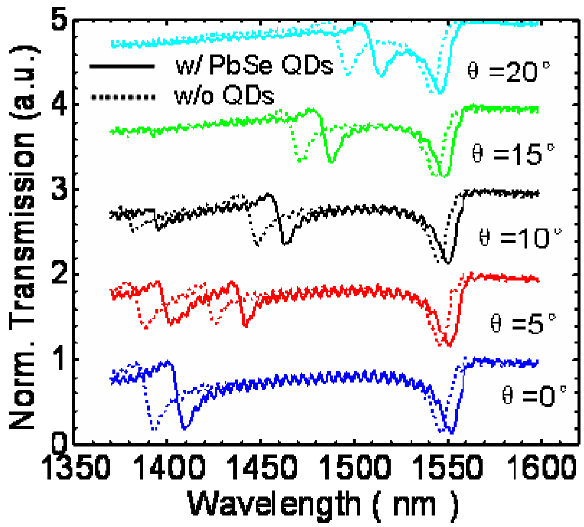

Figure 7 Measured incident angle θ dependent transmission along with ψ=0°, ϕ=0° for SiNM on glass substrate; solid and dash cuves accounts for with and without PbSe QDs respectively.

4 CONLUSIONS

In conclusion, we have fabricated silicon Fano filters on glass and on PET substrates, based on the wet transfer process. We have investigated the infrared absorption characteristics for PbSe colloidal quantum dots in such transferred Si PC cavities, via Fano resonances. Polarization independent filter was achieved by PC cavities with or without PbSe QDs. In addition, PbSe QDs in PC cavities result in 8nm red-shift as well as absorption change in the spectra response because of interaction between PbSe QDs and PC cavities. These findings enable the design of spectrally selective photodetectors at near infrared regime with the desired angle and polarization properties.

5 ACKNOWLEDGEMENTS

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